

# Grand Challenges in the Physics of the Sun and Sun-like Stars

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## 1 INTRODUCTION

“If the Sun had no magnetic field, it would be as uninteresting as most astronomers think it is”. This statement is attributed to R. B. Leighton [1]. Personally I think the Sun is of enormous interest in all respects, magnetic and non-magnetic; nonetheless, the grand challenges I have selected for this article do indeed pertain to the Sun’s magnetic field.

The study of stellar structure and evolution is one of the main building blocks of astrophysics, and the Sun has an importance both as the star that is most amenable to detailed study and as the star that has by far the biggest impact on the Earth and near-Earth environment through its radiative and particulate outputs. Over the past decades, studies of stars and of the Sun have become somewhat separate. But in recent years, the rapid advances in asteroseismology, as well as the quest to better understand solar and stellar dynamos, have emphasized once again the synergy between studies of the stars and the Sun. In this article I have selected two “grand challenges” both for their crucial importance and because I think that these two problems are tractable to significant progress in the next decade. They are (i) understanding how solar and stellar dynamos generate magnetic field, and (ii) improving the predictability of geo-effective space weather.

## 2 SOLAR AND STELLAR DYNAMOS

*How does the Sun generate its periodically reversing large-scale magnetic field? How do other solar-like stars generate their magnetic fields, and what are the similarities and differences between stellar activity cycles and that of the Sun? What can be learned about the solar dynamo by studying other stars?*

One of the most evident manifestations of solar magnetism is the number of sunspots, which waxes and wanes with an approximately 11-year quasi-periodic cycle. Once the polarity flip between 11-year cycles is taken into account, this becomes an approximately 22-year cycle. The Sun’s large-scale ambient field, which is predominantly dipolar, has a similar 22-year cycle. Sunspots occur where concentrations of magnetic flux poke out through the Sun’s surface, inhibiting the convection and causing that portion of the surface to be cooler (and hence darker) than its surroundings. Sunspots often occur in identifiable bipolar pairs, roughly oriented along lines of constant latitude but with the leading spot typically closer to the equator. The polarity of the leading spot is oppositely signed in the two hemispheres, and moreover changes sign every approximately 11 years.

The number of sunspots reaches a maximum approximately every eleven years, though the cycle length is quite variable. Also, the number of sunspots at maximum is very variable. There can also be extended

periods when the sunspot cycle appears to turn off, notably in the Maunder minimum of approximately 1645-1715, and proxies for solar activity such as isotope deposits in ice cores suggest that such “grand minima” occur occasionally and apparently randomly in the Sun’s past.

How the Sun generates its oscillatory magnetic field is, however, not yet understood. The appearance of pairs of sunspots of opposite polarity is strongly suggestive of magnetic flux tubes rising from the interior and that these tubes are approximately aligned parallel to the solar equator, i.e., the field they contain is *toroidal*. The large-scale but weaker field is *poloidal*. It seems likely that in some way the cycling large-scale magnetic field of the Sun involves a dynamo in the course of whose operation toroidal field is converted to poloidal field and poloidal field is converted to toroidal field. Typically, generic dynamo models involve stretching, twisting and folding of the magnetic field [e.g. 2].

There are a number of models for how the Sun continues to generate a large-scale magnetic field via dynamo action, but none at this point is anything more than a cartoon of what may be taking place. Many are “mean-field dynamos”, which are based on the assumption that one can make a separation of scales between the large scale on which one wishes to describe the evolution of magnetic field, and the small-scale interactions of magnetic field and plasma motions that ultimately get parametrized in some closure scheme [e.g. 3]. Some often-invoked elements for the solar dynamo are differential rotation in the solar interior, which stretches out the poloidal field to produce toroidal field, and the convective motions that take place in the convective envelope of the Sun, which may take toroidal field and produce poloidal field via the so-called *alpha* mechanism. Helioseismology has mapped the rotation in much of the solar interior [e.g. 4, 5]. Helioseismology has also established that the convective envelope occupies the outer 30 per cent of the solar interior [6], and that the base of the convection zone roughly coincides with a region of rotational shear that is now called the tachocline [e.g. 7].

The state of understanding of the solar dynamo has been reviewed by e.g. [8], [9] and [10]. A class of models that is currently popular in solar physics is the “flux transport dynamo model” [11, 12]. These models are mean-field models that invoke the Babcock-Leighton mechanism in which the near-surface motions of differential rotation and meridional circulation statistically convert the toroidal field in decaying sunspots into a poloidal field. Meridional circulation sets up a conveyor belt that advects this field to high latitudes, then subducts it to the base of the convection and transports it towards the equator, during which passage it gets converted to toroidal flux that rises to the surface when it gets strong enough to be magnetically buoyant and forms sunspots.

Shortcomings of present-day models of the solar dynamo are that they are either highly idealized mathematical or computational models that possibly elucidate some of the principles but do not yet match the solar behavior; or they have *ad hoc* parameters that can match the observed large-scale behavior (e.g. sunspot number) but have little or no predictive power. That we are still far from a robust predictability is well illustrated by the wide range of predictions for the amplitude of Cycle 24 [13], most of which inevitably were incorrect.

Recent developments include numerical models of the solar convection zone and outer radiative interior that capture the convective motions and rotation and begin to show cycling dynamo behaviour [14, 15, 16, 17], though they do not yet succeed in producing solar-like behavior: either they need a rotation rate that is far greater than that of the Sun, or they produce cycle periods that are longer than the Sun’s. Nonetheless this line of research is promising. Understanding the solar dynamo is certainly a Grand Challenge.

Other stars are also observed to exhibit magnetic activity cycles [e.g. 18, and references therein], and seeking to understand stellar activity cycles and the Sun’s dynamo in the context of those of other stars is a promising line of attack on the solar dynamo problem. Asteroseismology is opening up the study of stellar interiors, analogous to the impact of helioseismology on solar interior studies, and the *Kepler* mission in particular has made a step-change in the subject [e.g. 19, 20, 21, 22, 23, 24]. For a summary of early and more recent asteroseismic results from the *Kepler* mission, see, respectively, [25] and [26]. For understanding stellar dynamos and the physical ingredients for dynamo action, asteroseismology provides a valuable complement to traditional spectroscopy and accurate photometry, which themselves are extremely useful for measuring stellar surface rotation rates and latitudinal differential rotation, as well

as revealing activity cycles similar to that of the Sun. A puzzle still to be resolved is that the Sun appears to be anomalous in the context of other stellar dynamos. As shown by [27], activity cycle periods in a variety of other stars seem to fall onto two branches: those for which the cycle period  $P_{\text{cycle}}$  is about 400 times as long as the rotational period  $P_{\text{rot}}$  of the star, and those for which  $P_{\text{cycle}}$  is about 90 times as long as  $P_{\text{rot}}$ . Some stars seem to have two periods in their activity, one falling on each of two branches. This finding suggests there may be two basic dynamo modes in stars. The Sun's 11-year cycle and approximately 26-day rotation period puts it on neither of these branches, but rather intermediate between the two. Interestingly, the Sun seems to exhibit a secondary period of about 2 years in some of its activity indices, which would mean that the Sun's two activity periods are in a ratio that is not dissimilar to 400:90. There is much still to be understood.

### 3 IMPROVING THE PREDICTABILITY OF SPACE WEATHER

*What causes large potentially Earth-impacting space weather events on the Sun and how can we better predict them? What improvements, especially in terms of observations of the solar atmosphere and its magnetic field, can we foresee to improve forecasts of the geo-effectiveness of such events?*

As our nearest star, the Sun has a dominant influence on the Earth and near-Earth environment. One particular class of solar influences on the Earth is known collectively as space weather, magnetically driven episodic variations in the Sun's radiative and particulate outputs that impact on the Earth and geospace. The potential societal impacts of space weather – on power grids, on communications and GPS, on satellites, on airline crew and passengers, on humans in space – are increasingly recognized [28].

The Sun's role as the driver of space weather is evident, but we have only a poor understanding of the physics that actually triggers the most impactful space weather eruptions – X-class flares and coronal mass ejections (CMEs) – and we have little capability to predict when such events will occur and how geo-effective they will be. To the latter point, it is particularly important to be able to determine whether the embedded magnetic field in an Earthward-directed CME will be northward or southward, since the southward case is much more impactful as it interacts with the Earth's magnetosphere.

Advances are needed in a number of key areas. New instrumentation and analysis tools are required to better observe the Sun's chromosphere and corona and hence to determine the plasma conditions and magnetic fields there. In contrast, the photosphere is relatively well observed and understood, though even there recent observations have thrown up surprises and controversy, such as the finding from Hinode satellite observations that the small-scale magnetic field is apparently predominantly horizontal rather than vertical [29].

The Daniel K. Inouye Solar Telescope (*DKIST*), formerly known as the Advanced Technology Solar Telescope (*ATST*), will be the largest ground-based solar telescope and will provide extremely high resolution observations of the Sun's photosphere, chromosphere and corona, but only in a very small field of view [30]. Though with its small field of view it will not provide a forecasting capability for space weather, a major justification for *DKIST* is to observe and lead to an understanding of the small-scale drivers of space weather events. In my view, a key component for predicting the onset of large flares and possibly CMEs is also a knowledge of the near subsurface emergent magnetic field and plasma flows, and the only viable means of detecting these is local helioseismology [31]. There is evidence that the onset of major flare activity is preceded by an increase in kinetic helicity in the subsurface region [32, 33]. Advances require improved local helioseismic analyses, particularly in regions of strong magnetic field [e.g. 34]. Overall, a complete picture will likely require better theoretical understanding of the roles of a number of different elements – magnetic field-line footpoint motions in the photosphere, new emergent flux, and the complexity of existing magnetic fields in the solar atmosphere – in the genesis of space-weather events.

The chromosphere constitutes a boundary layer between the photosphere and solar interior on the one side and the corona and heliosphere on the other. It is the most poorly understood region of the solar

atmosphere: it is highly dynamic in nature [e.g. 35], and the approximation of local thermodynamic equilibrium (LTE) is inadequate for modeling the observations there. Yet it is a region through which mass and energy fluxes from the Sun must pass, and it can be argued that the chromosphere rather than say the photosphere is the true bottom boundary for modeling the heliosphere and understanding space weather. [36] provides a good overview of the challenges and opportunities for advancing understanding of the chromosphere and also gives context from chromospheres of other stars. Spectro-polarimetric observations in multi-wavelengths of the spectral lines formed in the solar chromosphere are one key to advancing understanding of this region, and a number of instruments have been or are being developed and deployed to make such observations. These include several of the first-light instruments to be deployed on the *DKIST*, the *CRISP* instrument at the Swedish Solar Telescope [37], and the Chromosphere and Prominence Magnetometer, *ChroMag* [38]. Development of non-LTE spectro-polarimetric inversion codes [e.g. 39] is also essential for the interpretation of the observations from the new suite of instruments.

It is evident from the spectacular loop structures observed there that the corona is dominated by magnetic fields, but direct measurements of the magnetic field in the corona are very challenging and are only now being realized [40]. Such measurements over extended spatial regions, complemented by magnetic field measurements in the chromosphere, promise to provide knowledge of the magnetic field in CMEs as they leave the Sun, thus perhaps making possible the forecasting of the magnetic field strength and direction in the sheaths and cores of Earth-impacting CMEs. Spectro-polarimetric observations in emission lines formed in the corona and observations at radio wavelengths provide two complementary avenues for coronal magnetic field measurements. The proposed Frequency Agile Solar Radiotelescope (FASR) will observe the corona at radio wavelengths [41]. Observations in the near-infrared will be made by the *DKIST* (again, only in a small field of view) and by the proposed Coronal Solar Magnetism Observatory coronagraph (*COSMO*) [42]. A prototype for the *COSMO* coronagraph, the Coronal Multi-Channel Polarimeter (*CoMP*), is currently making daily spectro-polarimetric observations in the near-IR and has demonstrated that it is possible to measure the magnetic field in the corona [43, 44]. Modeling of observations to reconstruct the coronal magnetic field by tomographic or other techniques looks promising [45].

## 4 OTHER ISSUES

I have chosen the above two areas of major challenge because of their importance and because I believe that significant progress on them can be made in the next decade. No doubt, another author could have picked two other but equally fascinating areas of challenge. In closing, I would just like to mention a further set of issues that are undoubtedly important for improving our understanding of the Sun and Sun-like stars.

Since around 2005, there has been an “abundance problem” with the Sun. Prior to that date, solar models constructed with the then-current estimates of the Sun’s chemical abundances were in good agreement with helioseismology. But new spectroscopic analyses and 3-D atmospheric modeling by [46] revised significantly downwards the solar heavy-element abundance, particularly the oxygen abundance. This resulted in a much worse agreement between solar models and the Sun’s internal stratification as inferred from helioseismology [47]. Subsequent spectroscopic re-evaluations of the solar abundances, though they have revised upwards slightly the values originally published by Asplund et al., still give a significantly lower heavy-element abundance than pre-2005, and attempts to modify the microphysics assumed in 1-D stellar models have not resolved the discrepancy with helioseismology [48]. A number of current attempts are underway in 2-D and 3-D models to incorporate macrophysics that has not to date been part of the standard solar and stellar models. These include incorporating rotation, magnetic fields, and internal gravity waves [e.g. 49, 50, 51, 52]. These additional physical effects can variously redistribute angular momentum and chemical abundances within the stellar interior. Asteroseismology provides constraints on what can be assumed [53, 54]. My own view is that fully incorporating these effects into models, particular in 3-D, may take rather longer than a decade. Nonetheless it is excellent that these modeling

efforts have begun, and there will be a rich interplay between the modeling and asteroseismology for years to come.

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